Double white dwarfs and *LISA*

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Abstract. Close pairs of white dwarfs are potential progenitors of Type Ia supernovae and they are common, with of order 100 − 300 million in the Galaxy. As such they will be significant, probably dominant, sources of the gravitational waves detectable by *LISA*. In the context of *LISA*'s goals for fundamental physics, double white dwarfs are a source of noise, but from an astrophysical perspective, they are of considerable interest in their own right. In this paper I discuss our current knowledge of double white dwarfs and their close relatives (and possible descendants) the AM CVn stars. *LISA* will add to our knowledge of these systems by providing the following unique constraints: (i) an almost direct measurement of the Galactic merger rate of DWDs from the detection of short period systems and their period evolution, (ii) an accurate and precise normalisation of binary evolution models at the shortest periods, (iii) a determination of the evolutionary pathways to the formation of AM CVn stars, (iv) measurements of the influence of tidal coupling in white dwarfs and its significance for stabilising mass transfer, and (v) discovery of numerous examples of eclipsing white dwarfs with the potential for optical follow-up to test models of white dwarfs.

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1. Introduction

In the early 1980s it was suggested that Type Ia supernovae might come from close pairs of white dwarfs merging under the action gravitational radiation losses (Webbink 1984, Iben & Tutukov 1984). It was later realised that the large number of systems needed to sustain the Type Ia rate within the Galaxy under these models meant that double white dwarfs (henceforth DWDs) are likely to be a dominant source of gravitational waves for space-based interferometry, to the extent that over some frequency intervals of interest in the context of *LISA*, DWDs may define *LISA*'s noise floor (Evans et al. 1987, Hils et al. 1990).

Early searches for DWDs produced meagre returns, and predictions that 10% of all "single" white dwarfs might in fact be double (Paczynski 1985) seemed wide of the mark. Robinson & Shafter (1987) found no DWDs amongst 44 targets, Foss et al. (1991) none amongst 25, and Bragaglia et al. (1990) found one certain DWD together with a few candidates from 54 targets. Together with the system L870-2, discovered by Saffer et al. (1988), by the early 1990s only two DWDs had measured periods. This changed when advances in our understanding of white dwarf atmospheres led to the identification of white dwarfs of too low a mass for single star evolution (Bergeron et al. 1992). Optical spectroscopy showed that a large fraction of these objects are DWDs (Marsh 1995, Marsh et al. 1995, Holberg et al. 1995, Moran et al. 1997, Maxted et al. 2000). Since the turn of the millennium further discoveries have followed from the SPY survey (Napiwotzki et al. 2004) and from the SDSS as detailed later.

These discoveries have established the presence of large numbers of DWDs and their importance as gravitational wave sources. There have been numerous studies of the likely impact of DWDs on *LISA*. These find that below a cutoff frequency of about 2 to 6 mHz, there are so many systems that their signals are unresolved, while above this frequency individual systems are resolved, with the odd nearby system rising above the noise at somewhat lower frequencies (Hils et al. 1990, Hils & Bender 2000, Nelemans et al. 2001, Ruiter et al. 2010, Liu et al. 2010, Yu & Jeffery 2010).

Most of these studies have been concerned with predicting the gravitational wave (GW) signal from DWDs in *LISA*. My interest here is more what we can learn about DWDs from *LISA* that is hard to deduce from electromagnetic (EM) observations. The potential is great, with direct measurement of tidal coupling between white dwarfs and the first detections of DWDs in globular clusters where their numbers are expected to be dynamically enhanced (Shara & Hurley 2002), likely to come from *LISA* data.

2. The two types of double white dwarfs

DWDs split into two groups which have different properties, from both the EM and GW perspectives, although in each case the two groups, while physically distinct, can be difficult to distinguish observationally. The two groups are the detached and semi-detached DWDs. Detached DWDs are simple pairs of white dwarfs evolving

towards shorter periods under the action of gravitational wave losses. The semi-detached systems, observationally identified as the AM CVn stars (see Solheim (2010) for a recent review), are systems in which stable mass transfer takes place from a Roche-lobe filling hydrogen-deficient star to a more massive companion white dwarf. From now on I will refer to all such systems as AM CVn stars. Hydrogen deficiency is necessary to reach short orbital periods; the hydrogen-rich counterparts to AM CVn stars are the cataclysmic variable stars which reach a minimum orbital period of around 80 minutes; I do not consider these further here. The Roche-lobe filling stars in the AM CVn stars must be at least partially degenerate to reach very short orbital periods. White dwarfs fit the bill, and although these systems are not necessarily "double white dwarfs" for simplicity I will continue to use the umbrella term "DWDs" for both classes.

The key difference between these two classes from an EM point of view is the presence of accretion in the AM CVn stars which can produce X-rays, atomic line emission and photometric variability. This is both a blessing and a curse: a blessing as it makes these systems, which are rare, easier to find, and a curse because we don't understand accretion well enough to estimate selection effects with certainty. From a GW standpoint, the key differences are (a) the system masses which in the case of the AM CVn stars can reach very low values ($< 0.1\,\mathrm{M}_{\odot}$) inaccessible to the detached DWDs, and (b) the time derivatives of the gravitational wave frequencies which on the whole will be negative for the AM CVn stars but always positive for the detached DWDs.

3. Detached DWDs

For *LISA*, detached DWDs (for this section I will drop the "detached" qualifier) will probably be the single dominant source class, the "main sequence" of space-based gravitational wave astronomy. They are a class of huge current interest as they are the candidate progenitors of Type Ia supernovae usually referred to as the "double degenerate" (DD) scenario (Webbink 1984, Iben & Tutukov 1984). The fortunes of DWDs as Type Ia progenitors have waxed and waned over the years when squared up against the "single degenerate" (SD) model which supposes accretion from a hydrogen rich companion (Whelan & Iben 1973, Nomoto 1982). Recent papers continue to show a lack of consensus (Gilfanov & Bogdán 2010, Di Stefano 2010) and it is of course possible that there are multiple progenitor classes, as suggested by evidence for bimodality in the delay time distribution of Type Ias (Mannucci et al. 2006, Ruiter et al. 2009).

The early failures to find many DWDs have often been raised to argue against DDs as potential Type Ia supernova progenitors (Branch et al. 1995, Hachisu et al. 1999), indeed, this perception remains current (Parthasarathy et al. 2007). My view is that, within the admittedly rather large margins of error, this is not a huge problem given that DWDs with short merger times and ones with total masses close to the Chandrasekhar limit have been discovered (Moran et al. 1997, Napiwotzki et al. 2002, Karl, Napiwotzki, Nelemans, Christlieb, Koester, Heber & Reimers 2003). It is perhaps not often realised that the current sample of DWDs remains strongly biassed towards low mass systems

Table 1. Detached double white dwarfs ordered by orbital period. The references are to the discovery papers. Objects starting with 'J' are SDSS white dwarfs.

Name	P days	M_1 $M_\odot$	M_2 $M_\odot$	Rf	Name	P days	M_1 $M_\odot$	M_2 $M_\odot$	Rf
J1053+5200	0.043	0.20	> 0.26	1	PG1713+332	1.127	0.35	> 0.18	5
J1436+5010	0.046	0.24	> 0.46	1	WD1428+373	1.157	0.35	> 0.23	15
WD0957-666	0.061	0.37	0.32	2	WD1022+050	1.157	0.39	> 0.28	15
J0849+0445	0.079	0.17	> 0.64	3	WD0136+768	1.407	0.47	0.37	16
WD1704+481	0.145	0.39	0.56	4	WD1202+608	1.493	0.3	> 0.25	17
PG1101+364	0.145	0.36	0.31	5	WD0135-052	1.556	0.47	0.52	18
PG2331+290	0.166	0.39	> 0.32	6	WD1204+450	1.603	0.46	0.52	16
J1257+5428	0.190	0.20	> 0.95	7, 8	WD0326-273	1.875	0.51	> 0.59	12
NLTT 11748	0.236	0.15	0.71	9	WD1349+144	2.209	0.44	0.44	19
J0822+2753	0.244	0.17	> 0.76	3	HE1511-0448	3.222	0.48	> 0.46	12
HE2209-1444	0.277	0.58	0.58	10	PG1241-010	3.347	0.31	> 0.37	6
J0917+4638	0.316	0.17	> 0.28	11	PG1317+453	4.872	0.33	> 0.42	6
WD1013-010	0.437	0.44	> 0.38	12	WD2032+188	5.085	0.41	> 0.47	6
HE1414-0848	0.518	0.71	0.52	13	WD1824+040	6.266	0.43	> 0.52	15
WD1210+140	0.642	0.23	> 0.38	12	WD1117+166	30.09	0.7	0.7	20
LP 400-22	1.010	0.19	> 0.41	14					

1. Mullally et al. (2009), 2. Moran et al. (1997), 3. Kilic et al. (2010), 4. Maxted et al. (2000), 5. Marsh (1995), 6. Marsh et al. (1995), 7. Badenes et al. (2009), 8. Kulkarni & van Kerkwijk (2010), 9. Steinfadt et al. (2010), 10. Karl, Napiwotzki, Nelemans, Christlieb, Koester, Heber & Reimers (2003), 11. Kilic et al. (2007), 12. Nelemans et al. (2005), 13, Napiwotzki et al. (2002), 14. Kilic et al. (2009), 15. Morales-Rueda et al. (2005), 16. Maxted, Marsh & Moran (2002), 17. Holberg et al. (1995), 18. Saffer et al. (1988), 19. Karl, Napiwotzki, Heber, Lisker, Nelemans, Christlieb & Reimers (2003), 20. Maxted, Burleigh, Marsh & Bannister (2002).

because these were specifically targeted in the searches that started in the 1990s as well as in more recent searches. Similarly, the enormous difference in our ability to find DD versus SD progenitors should not be underestimated: while it is possible to see potential SD Type Ia progenitors in other galaxies (although not necessarily to recognise them as such), it is hard to follow DWDs using EM observations if they are more than a few hundred parsecs away: finding DWDs is hard work. The best prospect for an observational calibration of DWD numbers is offered by the SPY survey (Napiwotzki et al. 2004) that did not target particular mass ranges, although even it suffers unavoidable selection biases with respect to both mass and temperature that need allowing for.

To understand what *LISA* can bring to the study of DWDs, it is important to know first what EM observations can tell us. Table 1 lists the periods and masses of DWDs with published orbital periods. The mass of the brighter component can usually be measured by modelling its optical spectrum. Sometimes both components are visible

and then both masses can be measured, but often one can only deduce a lower limit to the mass of the unseen component from the orbital motion of its companion. One can sometimes measure the temperatures of both components and thus the difference between the formation times of each component, a strong discriminator of the prior evolution (van der Sluys et al. 2006). The number of detached DWDs in the Galaxy can approximately be estimated from the fraction of systems observed to be DWD and the total number of white dwarfs in the Galaxy. This approach gives a number of systems ranging from 20 to 200 million (Maxted & Marsh 1999, Holberg et al. 2008). Binary population synthesis studies have given numbers from around 100 to 400 million (Han 1998, Nelemans et al. 2001, Liu et al. 2010, Yu & Jeffery 2010).

In comparison with the best EM observations, *LISA* will give us comparatively limited information on individual systems, yet there are several ways in which *LISA* can provide greatly superior information on DWDs as a whole, as I now discuss.

3.1. Population statistics

At high enough frequencies, *LISA* will be sensitive to DWDs throughout the Galaxy and will give us a view of the whole population with relatively little selection. Several studies have predicted that $\sim$ 10,000 DWDs should have high enough frequencies to be resolvable by *LISA* (Nelemans et al. 2001, Ruiter et al. 2010). These will be the shortest period systems, which are those of most relevance to the merger rate of DWDs, a quantity of great interest in the context of Type Ia supernovae. EM observations, which are only sensitive out to a limited distance, will always be handicapped in comparison. Assuming a single chirp mass, $M_c = M_1^{3/5} M_2^{3/5} (M_1+M_2)^{-1/5}$, the flux of DWDs crossing orbital period P at a time t_0 since the formation of the Galaxy is given by

$$F(P, t_0) = -n(P, t_0)\dot{P} = \int_P^{P_m} B(P', t_0 - \tau(P' \to P))\, dP', \tag{1}$$

where $\tau(P' \to P)$ is the time taken for a system to change period from P' to P, $n(P, t)$ is the orbital period distribution and $B(P, t)$ is the birth rate period distribution at time t. A more realistic model would require integration over the distribution of chirp masses as well. The upper period limit P_m is set by the maximum period that is able to evolve to period P within the lifetime of the galaxy, i.e.

$$\tau(P_m \to P) = t_0. \tag{2}$$

For the short period systems that we are interested in for *LISA*, P_m is around 5 to 15 hours. As we approach short periods ($P \to 0$) P_m will tend to a constant and thus the flux $F = -n\dot{P}$ will tend to a constant, i.e. the DWD merger rate. The numbers per unit period then scale as $n \propto 1/\dot{P}$, or equivalently $n \propto \tau_m/P \propto P^{5/3}$ where τ_m is the merger time at period P

$$\tau_m = 1.00 \times 10^7 (M_c/\mathrm{M}_\odot)^{-5/3} (P/1\,\mathrm{h})^{8/3}\,\mathrm{yr}, \tag{3}$$

assuming that we can neglect the effect of tides, although these are likely to be significant at these short periods (Willems et al. 2007). The rapid reduction in lifetime with period

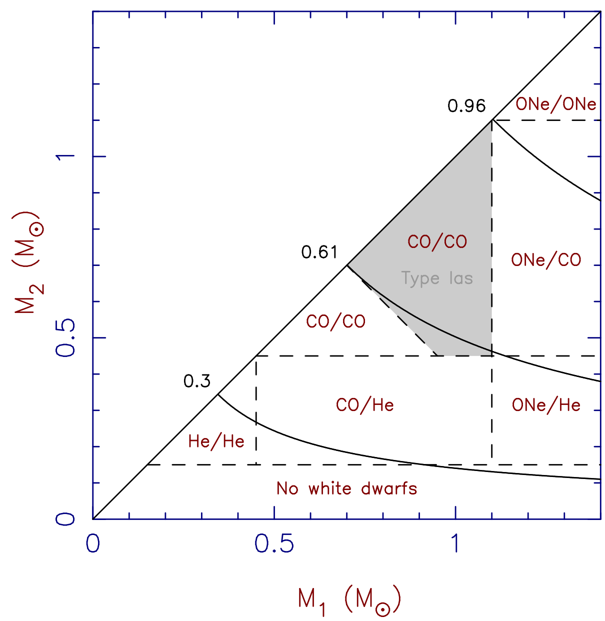

Figure 1. The curved lines are lines of constant chirp mass; the straight regions delineate different pairs of DWDs, assuming a unique mapping between bulk composition and mass: He $= 0.15 - 0.45$, CO $= 0.45 - 1.1$, ONe $= 1.1 - 1.4\,\mathrm{M}_\odot$.

makes it hard for EM-based searches to probe the short-period end of the birth rate distribution directly; this was realised by Robinson & Shafter (1987) as the major caveat on their null result. Looking at Table 1, EM observations are unlikely to provide strong constraints upon the integrand of Eq. 1 for periods much below one hour. At such periods the merger times are of order 10 to 100 million years, depending upon mass, i.e. at least 100 times shorter than the age of the Galaxy, and still 20 times shorter than the time for which white dwarfs display strong spectral features. It is probably no coincidence that the shortest period systems known have low masses since this increases their survival time.

3.2. DWD sub-types

For some fraction of the resolved *LISA* sources, it will be possible to detect not just the frequency f, but its time derivative $\dot{f}$. For detached DWDs this is a function of period and chirp mass only. The best EM observations can return M_1 and M_2 separately, but *LISA* wins through the very large number of likely detections, sensitivity to those of high mass and short period, and well-understood selection effects. The outcome of DWD mergers depends upon their masses and their composition. For instance the canonical Type Ia model for DWDs involves the merger of two carbon-oxygen white dwarfs. To a large extent, the bulk composition of white dwarfs is thought to map into their mass. If so then, as Fig. 1 illustrates, chirp mass measurements have good potential when combined with population synthesis to discriminate the fraction of potential Type Ia supernovae, pairs of helium white dwarfs, etc. Example numbers are around 10,000 resolvable DWDs *LISA* (Nelemans 2003, Ruiter et al. 2010, Liu et al. 2010), around 600

of which will have detectable frequency changes within one year (Nelemans 2003, Ruiter et al. 2010), and presumably many more over longer intervals. The different types (He+He etc) lead to a very strongly structured chirp mass distribution illustrated in Fig. 7 of Liu et al. (2010) supporting the potential that chirp masses hold for probe DWD evolution.

4. AM CVn stars

In an AM CVn star, degenerate or semi-degenerate donor stars lose mass to white dwarf companions (note that there are similar systems, the ultra-compact X-ray binaries in which the accretors are neutron stars). As they do so, they expand, and the orbital periods lengthen. *LISA* sources with $\dot{f} < 0$ are therefore likely AM CVn stars. The known systems have orbital periods that range from just over 5 minutes to 65 minutes. Periods this short require the mass donors to be largely or entirely hydrogen-deficient in order to be dense enough to fit within their Roche lobes. Most known examples do indeed lack hydrogen, the exception being HM Cnc (Reinsch et al. 2007). A key unsolved issue for these systems is how they form. Attention has focussed on three types of progenitor: (i) detached DWDs, (ii) evolved cataclysmic variable stars, and (iii) white dwarf / helium star accreting binaries. At the long periods of most known systems, these three models lead to rather subtle differences in mass transfer rate and other parameters (Deloye et al. 2007) which even the best constrained systems are not yet capable of distinguishing (Copperwheat et al. 2010). We know DWDs of short enough period to merge within a Hubble time, while there are no clear progenitors of the other two routes. However, it is not obvious that DWDs will survive the onset of mass transfer because of the instability that can set in if the two white dwarfs are of a similar mass (Marsh et al. 2004). Indeed, until recently all DWDs of known mass ratio were candidates for merging (Fig. 2).

The differences are more marked at short periods. For instance, only DWDs are thought to be able to reach periods well below 10 minutes. HM Cnc ($P = 321\,\mathrm{sec.}$) is the only such system known (Ramsay et al. 2002, Roelofs et al. 2010). HM Cnc is optically faint and has a soft X-ray spectrum that could easily be absorbed if it were more distant. *LISA*'s sensitivity to short period systems holds great potential for finding more such systems and for elucidating the nature of their donors. This can first be carried out in a statistical manner through the frequency distribution of those systems with $\dot{f} < 0$. This may tell us the nature of the progenitors that survive the onset of mass transfer.

4.1. Spin–orbit coupling and AM CVn numbers

The degree to which detached DWDs survive mass transfer to live on as gravitational wave sources is highly dependent upon the degree to which angular momentum accreted onto the more massive component is fed back into the orbit (Marsh et al. 2004). Some theoretical studies have indicated that this coupling is strong and stabilising (Racine

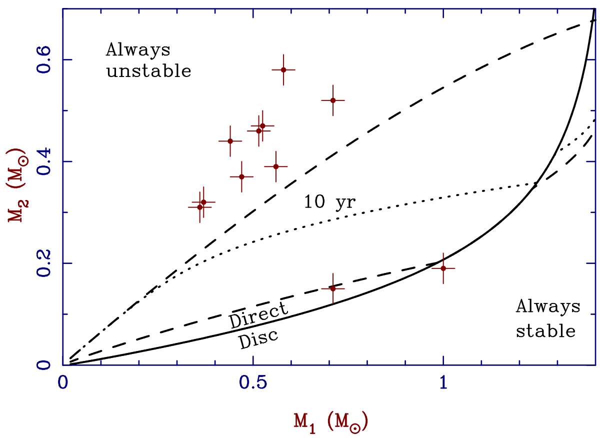

Figure 2. Stability regions for mass transfer between two white dwarfs (from star 2 to star 1), based on Marsh et al. (2004) with systems of known mass from Table 1 over-plotted. The upper dashed line marks the dividing line between stability and instability if the accretor does not gain angular momentum, while the lower solid line applies if it is not coupled to the orbit. Until the recent discoveries of the two systems lowest on the plot, all known systems were unconditionally unstable.

et al. 2007, Motl et al. 2007), while others suggest that much of the angular momentum can be fed back even in the absence of tidal coupling between the stars (Sepinsky et al. 2010). However the best observational calibration of the space density of AM CVn stars gives a space density around a factor of 10 lower than previously assumed, and around 250 times lower than that of the detached systems, suggesting perhaps that in fact many detached DWDs do not survive mass transfer (Roelofs et al. 2007). This issue is not settled but is another that *LISA* is ideally suited to answer: the ratio of systems with $\dot{f} > 0$ to those with $\dot{f} < 0$ as a function of f will be of great interest for addressing this question.

Although one can probably assume that a system with $\dot{f} < 0$ is an AM CVn star, the reverse is not true, i.e. $\dot{f} > 0$ does not imply a DWD, even if we expect this to be the case more often than not. AM CVn stars must pass through an initial phase during which $\dot{f} > 0$. Indeed it is possible that the two shortest period candidate AM CVn stars, HM Cnc and V407 Vul, are in precisely this phase as both have decreasing orbital periods (D'Antona et al. 2006, Deloye et al. 2007). As first pointed out by Webbink & Han (1998), and further investigated by Nelemans et al. (2004) and Stroeer et al. (2005), the "braking index" $n = f\ddot{f}/\dot{f}^2$ is an interesting parameter in these cases. For pure GWR-driven evolution, $n = 11/3$; we expect $n < 11/3$ during the turn-on phase of AM CVn stars, and during some phases $n < 0$. The second derivative $\ddot{f}$ leads to a cubic dependence of binary phase on time, which places a high value on extending *LISA*'s lifetime for as long as possible: without it we will not be able to distinguish detached DWDs from early-phase AM CVn stars except on a statistical basis, or perhaps through optical follow-up of nearby systems.

The braking index has one further use. The standard $n = 11/3$ value for detached DWDs treats the two stars as point masses, but as they approach the onset of mass

transfer we can expect the effects of tidal spin–orbit coupling to become significant (Willems et al. 2008), in effect acting as an additional sink of orbital angular momentum. Scaling as a high inverse power of the separation, tidal losses will act to increase the value of n. *LISA* detections of systems with $n > 11/3$ may therefore provide a direct indication of the significance of tidal coupling effects between white dwarfs.

5. Combined EM & GW observations

A significant number of the DWDs that *LISA* will see are potentially detectable through optical observations. Several hundred with $V < 24$ are predicted (Nelemans 2009). The bias towards short periods means that many will eclipse (Cooray et al. 2004) (although the first, and at the moment only, eclipsing detached DWD known, NLTT 11748, Steinfadt et al. (2010), has a surprisingly long 5.6 hour period). Eclipsing systems allow measurement of the scaled radii, R_1/a and R_2/a. Moreover, they permit precise optical timing measurements which are quite capable of determining the conjunction phases to within < 0.01 cycles within a single night of observation. Optical follow-up of such systems could add significantly to the numbers of systems for which we know the first and second derivatives, $\dot{f}$ and $\ddot{f}$, and hence the braking index n. The first challenge, as recognised by Cooray et al. (2004), will be to locate them once *LISA* has signalled their presence, but with projects such as the *LSST* underway, this seems feasible, even given the large-by-optical-standards *LISA* error boxes. Photometric measurements alone have the capability to determine the orbital inclination i as well as the scaled radii. Using mass-radius relations this could determine the mass ratio, which combined with the chirp mass can lead to the two masses, giving a major insight into the past evolution of the binaries. Spectroscopic observations will be difficult given the faintness and short periods of most of the *LISA* targets. However, it should be noted that purely photometric observations may well be able to return kinematic information entirely equivalent to spectroscopy through Doppler beaming. This has already been detected in the DWD eclipser, NLTT 11748, (Shporer et al. 2010). This effect may even allow the identification of non-eclipsing optical counterparts using standard phase-locked detection techniques. In the best cases there will result a redundant set of constraints which will allow tests of white dwarf mass-radius models. The result could be a bonanza for white dwarf astrophysics and provide the best *LISA* calibration sources.

6. Conclusions

Double white dwarfs are predicted to be the dominant source population at *LISA* frequencies. *LISA*'s sensitivity to short orbital periods will allow the best estimates of the merger rates of these stars, tidal coupling of the two stars and answer questions about their evolution that are hard to solve at the longer periods favoured by electromagnetic observations. The dual combination of the GW and EM observations will be a powerful tool for probing white dwarf astrophysics.

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